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THE VENTILATION OF TUNNELS

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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INTRODUCTION

OBJECT OF VENTILATION.- The ventilation of tunnels, whether in the process of construction or in actual operation, is one of the troublesome problems presented to the engineer. In the one case the fumes arising from the blasting charges have to be removed as speedily as possible from the headings in order that no time be lost in cleaning away the broken rock; and, in the other case, the air vitiated by the gases arising from the combustion of coal has to be replaced by fresh air. From these facts it is seen that the main problem which arises, is to find a quick and economical method of expelling the foul air produced, and to replace it with a supply of fresh air in such quantities as to insure health to all workmen employed, and also an ample degree of safety from accidents to the daily traffic through the tunnel.

CONSIDERATIONS INVOLVED.- In view of these facts there are many considerations involved, and each has to be treated separately to suit the existing conditions at the tunnel. The most important of these questions that arise are: the amount of air that is required to be supplied in a given time in order that proper ventilation may be secured, the sources of foul air and its effect upon the men working in the tunnel, and the effect that a good ventilating system will have upon the traffic.

AMOUNT OF AIR REQUIRED.- The amount of air that is required to insure proper ventilation varies in the opinion of different engineers, but it has in general been conceded that so long as

the amount of carbon dioxide does not exceed 20 parts in 10,000 by volume of air, the air in the railroad tunnel is satifactory. This is about the same proportion that is found in closed assembly halls and churches after a long lecture, and it is known that so long as the amount of carbon dioxide does not exist in greater quantities no ill effects will be observed. Moreover, in a few cases men have been known to work in an atmosphere containing 30 parts of carbon dioxide in 1,000 parts by volume of air, an amount sufficient to extinguish a candle, and have felt no ill effects. However, such conditions are not advisable.

SOURCES OF FOUL AIR.- The sources of foul air are various. During construction noxious gases arise from the lamps and torches used to light the interior of the tunnels where electric plants are not used for lighting. The respirations of men and beasts also cause objectionable odors. However, the principle source of noxious gases is blasting, and the fumes that arise from the explosives are so dense that they must be cleared from the working face before the men are able to resume their work.

In the completed tunnel these gases arise from the combustion of coal. On this subject Francis Fox, M. Inst. C.E., says that from his experience the combustion of coal by a locomotive in its passage through a tunnel gives approximately 29 cubic feet of poisonous gases for each pound of coal that is consumed. Knowing the amount of fuel consumed per mile, and multiplying this amount by 29, then by 500, and dividing the product by the number of minutes in the interval between trains, will give the amount of air in cubic feet per minute that must be introduced into the tunnel.

GENERAL EFFECTS OF FOUL AIR.- The general effect of foul air in the tunnel upon the workman is to cause him to have headaches and in most cases nausea. Aside from any injury to his health that may be contracted from this effect, the economical considerations must be taken into account. In foul air the men necessarily work slower and the progress is retarded. In a well ventilated tunnel they are able to work with comfort and vigor. The progress is increased, and the additional cost of ventilating is more than compensated for by the additional amount of work that is accomplished in a given length of time.

GOOD VENTILATING SYSTEM IS ESSENTIAL.- During the operation of the tunnel a good ventilating system is essential. It clears the atmosphere in a comparatively short period of time, and allows an increase in traffic through the tunnel. The interior and especially the rails are kept free from moisture. Many accidents have been caused by slippery rails especially on steep grades. The dangers due to this cause, therefore, are entirely eliminated.

RESULTS OF POOR VENTILATION.- Engineers now recognize the necessity of a continuous change of air. This is necessary for two reasons, first, to maintain the purity of the air, second, to regulate the moisture which it contains and prevent it from collecting on the walls, where it causes a chilling sensation to one entering the tunnel. Furthermore, with a slow and uncertain movement of the air it may easily be cooled below the dew point and become saturated, in which state it would be disagreeable and unhealthful. This dampness also has the same affect upon the rails as indicated above. A damp interior causes a

rapid oxidation of the rails and decreases their life. Observations made upon the effects of oxidation of rails in the Box tunnel of the Great Western Railway showed that in this tunnel, which was poorly ventilated, the wear due to this cause averaged 2 1/2 pounds per yard per annum, as compared with 1/4 pound in the open air.

Many accidents have occured in tunnels due to poor ventilation. Some, directly caused by poor ventilation, where the engineer and fireman were rendered unconsious by the gases of combustion; and others, indirectly caused by the breaking of rails that were badly oxidized, or by rails made slippery by the humidity of the air. Several illustrations are given below of accidents that have resulted from the existence of such conditions in tunnels.

PRACCHIA TUNNEL.- The Pracchia tunnel, between Florence and Bologna in Italy, before the Saccardo system of ventilation was installed, will afford a good illustration of some of the results of poor ventilation mentioned above. The tunnel is 9,000 feet long and is built upon a gradient of 1 in 40. Under any conditions due to winds, the state of the tunnel is bad, but when the wind is blowing in at the lower end at the same time a heavy train is ascending the gradient, the air becomes so vitiated that it is almost unbearable. The engine in order to climb the grade must work with the regulators wide open and emit large quantities of smoke and steam which travels along with the train. The steam condenses and moistens the interior, causing the wheels to slip and possibly stops the train. Then the conditions of the air becomes suffocating. On one occasion a heavy train with two engines, conveying a royal party and their suite, arrived at the

upper exit of the tunnel with both engine drivers and firemen insensible.

PONTE DECIMO TUNNEL.- Another example of bad ventilation occured in 1898 at the Ponte Decimo tunnel near Genoa, Italy. In this case a heavy goodstrain with three engines was going through the tunnel when it slipped and cameto rest upon a steep gradient. The engineers and firemen were all rendered insensible by the unbearable conditions of the air. The train then ran back by gravity to the lower end of the tunnel and crashed into a passenger train which was waiting to ascend the gradient. The result caused 12 people to lose their lives and 40 others to be injured.

USUI RAILWAY TUNNELS.- On the Usui Railway in Japan several tunnels were built with a gradient of 1 in 15. When locomotives began running the difficulty of keeping up steam was very great andthe fires had to be forced to their utmost. Therefore, instead of burning 32 pounds of coal per mile as Mr. Francis Fox, M. Inst. of C.E. assumes from his experience in connection with the ventilation of tunnels; the coal consumption in trials conducted for the government was no less than 250 pounds per mile and in one case reached 268 pounds per mile. This caused the smoke to become so dense in the tunnel that two persons standing side by side upon the foot plate were unable to see each other. On a day previous to the trial the steam in one engine gave out and caused the engine to stop in one of the tunnels. The engineer was nearly choked and the natives had to lie face down upon the ballast in order to breath. To remedy these defects various schemes were proposed for ventilating the tunnels. A very primitive method

was finally adopted of hanging a curtain at the lower entrance and closing it as soon as the train had passed into the tunnel. This stopped the draft of air following the train to some degree and enabled the train to liberate itself from the gases as it passed up the grade.

VENTILATION DURING CONSTRUCTION

OPINIONS OF ENGINEERS.- Engineers in charge of the tunnels that have been built in recent years have seen the advisability of proper ventilation during construction. Good examples of this are found in the driving of the Cascade tunnel for the Great Northern Railway, in the notable Alpine tunnels, the St. Gothard and Simplon, and also in the Kellog tunnel at the Bunker Hill and Sullivan Mines in Idaho. Several other noteworthy examples could also be mentioned. Today there are very few tunnels constructed in which suitable means cannot be found for supplying fresh air to the working face..The supplying of fresh air to the working face has became more prominent in recent years and owes much of its developement to the modern use of high explosives and dense fumes arising therefrom. In the recent tunnels that have been constructed special attention has been given to this subject with very good results, particularly in contract work where it is an important item in the expense account that the driving progress as speedily as possible. Good examples of this have been brought out in the construction of the St. Gothard and Simplon tunnels, the daily progress of which greatly surpassed that of all tunnels built in years previous.

Not only is pure air advantageous for rapid progress in the work, but it is also essential to the health of the workmen employed. In actual practise these two conditions are dependent upon each other to a considerable extent.

CONDITIONS IN MODERN TUNNELING.- In modern tunneling, after a charge has been fired, the only time that can be considered lost, is that occupied in the removal of debris resulting from the explosion. Hence it becomes very important to clear the broken rock away in order that the drilling tools can be set to work and actual progress in drilling resumed. To accomplish this end it is essential to have a strong current of fresh air reach the working face almost immediately after the charge has been fired in order that the dense fumes may be quickly cleared from the headings. The methods of accomplishing these results will be dealt with farther along, when the separate methods are described. Pure air during construction is of vital importance for the welfare of the workmen. If he is compelled to work daily in an atmosphere containing a large percentage of carbon dioxide, the principle gas that arises from the combustion of explosives and decayed matter, he is affected with a drowsiness that he cannot overcome unless fresh air is furnished to him. When the workmen are in this condition, the work must necessarily progress much slower than it would otherwise; and besides, it is liable to inflict lasting injuries upon the men. Accidents also occur more frequently when such conditions exist than at other times. These, at times, prove to be costly to the contractor or company in charge of the work. Therefore in order to make rapid progress in the driving of tunnels, to carry the project through with the minimum cost, and to insure perfect health to the workmen, the foul air should be expelled at once and a goodly amount of frsh air supplied. On account of the first cost involved the contractor is likely to overlook these facts,

but when everything is taken into consideration the expense will be less in the long run.

The different types of tunnel ventilation during excavation will now be explained.

USE OF COMPRESSED AIR.- The use of compressed air in tunneling is employed only in subaqueous work, usually not more than 100 feet below the surface of the water. In this connection a device known as the air-lock has to be employed for passing from the outer air to the working chambers filled with the compressed air. This enables the workman to pass at will from one air pressure to another. In order that no injurious effects may result, a suitable length of time should elapse before he proceeds from one chamber to another. The chief danger in this regard is that the men may pass through the chambers in too great haste, not allowing proper time for equalization of the air pressure in the locks. This sudden transition from a high pressure to the normal atmospheric pressure affects the human organism and has proven fatal to some workmen, depending somewhat upon their constitution and physique before entering the lock. A strong and robust man is better able to withstand the effects than one who is weaker.

Dangers Involved.- In going from atmospheric pressure to higher pressure in the locks the air is absorbed by the blood and carries with it any gaseous impurities that it may contain. Thus if the air is high in carbonic-acid gas the blood receives that impurity. In coming out of the compressed air the persons must be locked out slowly. Should they come out quickly bubbles of air form around the outer parts of the body, and the blood coming

in contact with them has a tendency to coagulate. Ih the post mortem examinations on different people who have met death in this manner, the veins and arteries on being cut open were found to be filled with coagulated blood.

Amount of Pure Air Required.- The amount of air required for men working in compressed air chambers differs somewhat from that used in ordinary tunneling. It was seen that in the latter case 20 parts of carbonic acid per 10,000 parts by volume afforded satisfactory conditions for ordinary work, and that even some men had worked in 30 parts of carbonic acid per 1,000 parts by volume without feeling any ill effects. But in compressed air the conditions differ. In a working pressure of 20 pounds per square inch a percentage above 1 or 1 1/4 parts of carbonic acid in 1,000 parts by volume was felt by some men. To make an ample allowance for ordinary work, about 3,000 to 4,000 cubic feet per hour of pure air should be supplied to each man to insure good ventilation. Even less than this would do at 30 pounds pressure per square inch. Tests made along this line with an expert diver resulted in the proof that he was satisfied with only 250 cubic feet per hour. However, this is exceptional, and was probably due to the fact that he was more accustomed to such conditions than the average person would be.

Method of Ventilating.- The method in which the ventilating is carried on is quite simple. It is usually the case that air is pumped in at a little higher pressure than required to keep the water out of the caisson or shield. This enables the air to leak out around the edge of the working face and thus supplies a continuous circulation.

Other means are also employed. The air is pumped into the working chamber at the top and taken out under pressure from a pipe connection near the bottom. The first method, however, is the one usually employed, as the air leaking around the edge has a tendency to lubricate the shield and allow it to be moved along more easily.

In ordinary tunnel work compressed air is often employed indirectly as a means of ventilation. This, however, is used only in tunnels where compressed air tools and motors are used exclusively to carry on the work of construction; the principle being that the exhausts from the different air tools and engines will be sufficient to clear the headings and main cross sections from smoke and gases, and to render the atmosphere in the tunnel satisfactory for working conditions.

FANS.- In tunnel construction the heading is usually cleared by leading a tight but light weight pipe as near to the working face as possible, and then sucking or blowing out the foul air by means of a fan of suitable size, located at the portal or at the top of the shaft. In ordinary operations the working conditions do not warrant the use of more elaborate appliances, but in some cases, where the work is of great magnitude, as was that of the Simplon tunnel, a parallel tunnel of smaller dimensions than the main cross section may be driven, the two tunnels being joined at suitable intervals by means of cross cuts. The foul air at the headings can then be exhausted either through the main tunnel or through the smaller one at the side, or else fresh air can be forced directly into either tunnel. The methods used for exhausting the foul air will now be taken up.

Plant for Exhausting Foul Air.- The ventilating plant in this case consists of a suitable fan, or fans, together with all the necessary accessories for operating them successfully. The location of the fans should be near the portal or near the shaft of the tunnel, the location depending upon whether the portal or shaft is being used to carry on the work of construction. The fans should always be in such a position as not to interfere with the progress of the work.

Exhaust Pipe.- The pipe through which the foul air is exhausted should be of light construction, and made of a metal that does not corrode easily. The diameter of the pipe should be sufficient to allow a speedy withdrawal of all the fumes resulting from blasting. As a rule, the pipes are laid in sections, the lengths of the sections being governed by the existing conditions, but are usually never greater than 16 feet in length. The joints are made air tight and the whole pipe protected against mechanical injury by a suitable cover, usually made of boards. As a further protection it should be laid along one side of the tunnel where it will not interfere with the operations of the muck- and material- cars.

Where Used.- The form of tunnel in which this method is used for clearing the heading is that in which a single entry is being driven. It is also used at times in double entry tunnels when one of the headings has become far advanced through accidental delays that may have occured to the other. This forms a cheap and economical system for ventilating, and also one that does not require much time or labor in its construction and operation.

Cascade Tunnel.- In the case of the cascade tunnel the foul air was exhausted from the headings through a 24 inch galvanized iron pipe by means of a No. 9 Sturtevant fan running at 1700 revolutions per minute. These exhaust pipes were made in 16 foot sections and bolted together by cast iron rings with friction paper washers between the rings. The ventilation in this case was claimed to have been excellent, from 10 to 20 minutes being sufficient to clear the headings after a blast. In this case the supply of fresh cool air was increased materially by the large amounts of air liberated by the drills, hoists and pumps located near the heading.

The other method mentioned above, that of blowing in the fresh air directly through the tunnel and forcing the vitiated air out through the side drift or secondary tunnel, will now be considered.

The ventilating plant is similar to that mentioned above with the exception that no shafts are used, the fans always being located near the portals of the tunnel and arranged in such a manner that they may be used either as a blower or as an exhaust. In this connection the fans are usually arranged with suitable curtains and in such a manner that by simple operations of the curtains the air from the fans may be diverted from the tunnel to the side drift, or vice versa when the fan is acting as a blower. The same conditions also hold good when the fan is running as an exhaust, that is, the foul air may be exhausted either through the tunnel or side drift. The only tunnels in which this system of ventilating may be employed are those in which the double entries are being driven. The reason for this

is apparent at once, for were it not for the cross cuts and side drifts the fresh air forced into the tunnel would only dilute the gases and not force them out through the portal. But as it is, a complete circulation is produced and the gases are carried out with the air currents.

One of the most remarkable examples of this form of ventilation is found in the construction of the Simplon tunnel. This is one of the most notable tunnels ever constructed and besides is the longest ever driven, the total length being 12.4 miles.

Simplon Tunnel.- For ventilating the Simplon tunnel during and after construction a permanent ventilating plant, consisting of two 200 H.P. turbines and two fans 12.5 feet in diameter, was installed at each end of the tunnel. The arrangement of the two plants differed somewhat. At the Swiss end, which is located near the town of Brieg, the fans are placed one above the other close to the portal and the air passage carried across the roof of the tunnel. At the Italian end, near Isdle, the fans are placed one behind the other. The air passes first to a ventilator house and from there through a passage-way to the tunnel. Either plant can furnish a maximum of 106000 cubic feet of air per minute at a gage pressure of 9.85 inches of water.

The original plans of the Simplon tunnel were somewhat modified before construction work began. It was at first proposed to build two single track twin tunnels spaced 55.76 feet center to center, but later it was decided to open only one of the twin tunnels to its full dimensions and the other to about one-fifth the proposed size. The two were connected at intervals of 656 feet by a transverse gallery laid out on an angle of about 60 degrees

with the axis of the tunnel, this smaller tunnel or side gallery to serve for drainage, ventilating and other services connected with the work.

The ventilation of the tunnel during construction was accomplished in the following manner. Pure air was forced into the side gallery by the fans to the most advanced transverse gallery and then back through the main tunnel to the portal. A constant circulation was thus provided and all noxious gases carried out immediately. If the fans were run in the opposite direction, so as to exhaust the air from the side gallery, the direction of the air currents was reversed. In order that the air from the fans might be forced into either tunnel, a door was placed at the angle of the bifurcation. This door was operated either by hand or electricity and arranged in such a manner that either fork of the passage could be closed at will, thus causing the air to be forced into, or exhausted from, either the main tunnel or the side gallery. Sail cloth curtains operated in the same manner closed the portal of the tunnel. Later these sail cloth curtains were replaced by steel curtains.

As mentioned above the two curtains were connected at intervals of 656 feet, so that when the headings were advanced farther than the last transverse gallery a dead end resulted in that portion of the tunnel. When the distance was not too great, the exhaust air from the drills and pumps was sufficient to keep the air in good condition. If, however, the heading was too far advanced to insure good ventilation at the working face in this manner, another method was employed. A fan was placed in the last transverse gallery, and from there, the pure air coming from

the plant near the portal was forced through a 14 inch pipe up to the working face. The noxious gases were thus driven back toward the portal. In this connection it should be mentioned that the other transverse galleries were sealed as the work progressed to prevent a short circuiting of the air currents.

In driving the Simplon tunnel considerable heat was encountered in the rock and artificial means had to be used for cooling the headings. The method of cooling the air was practically the same at both ends. Cold water was pumped from the river Rhone at the Swiss end, and from springs encountered in the tunnel near the Italian end, through 10 inch pipe laid along one side of the service gallery. This pipe conducted the cold water to the working face where it was broken into a spray and cooled the air in the headings. In order that the water should remain cold until it reached the headings, the water pipe was insulated by jacketing it with a larger pipe and filling the annular space with charcoal.

As installed the ventilating plant at either end was much larger than required. Under usual conditions one fan operating so as to give a gage pressure of 2 1/3 inches of water furnished one cubic foot of fresh air per second to the working face. When this was increased to a gage pressure of 4 inches of water the current was strong enough to blow out the miner's lamps.

At the Italian end of the tunnel previous to the installation of the hydraulic plant mentioned above, a steam ventilating plant was installed near the ventilator house. This consisted of a 10 H.P. engine and a fan. The air was delivered from the fan to the service gallery through a pipe 20 inches in diameter.

When the fan was run at 1200 revolutions per minute it furnished 70 cubic feet of air per second at a gage pressure of 4 inches of water. This plant was kept in working order during the whole period of construction. The reason for this was that in case of accident to the main plant enough air could be supplied by this smaller plant to prevent a delay in the construction of the tunnel.

COMBINATION OF FANS AND COMPRESSED AIR.- The ventilation of tunnels during construction by means of a combination of fans and compressed air is probably used in most tunnels. The reason for this is apparent. In rock work considerable drilling must be done and one of the most economical methods of doing it is by means of compressed air tools. Water is often encountered that must be pumped out, and debris resulting from blasting has to be removed. All of this can be done with compressed air by using air pumps and engines. The advantages derived from their use are many. If steam drills, pumps and engines were used to perform the work mentioned above, more or less fumes would arise from the operations, the air in the tunnel would become suffocating, and a large amount of air would have to be furnished by fans in order to keep the interior cool and free from gases. If compressed air tools are alone used such conditions will not exist. In the operation of the different tools and engines the exhaust air is liberated into the tunnel. This is all fresh air that has been piped in from the fans located near the portal, and therefore has not been poluted by being brought in contact with noxious gases. Thus, instead of breathing the foul gases that would arise if other tools were used, the workmen

breath fresh air brought direct to them from the exterior of the tunnel. This method of feeding pure air from the air engines and tools seems to be very prominent among engineers and is the one generally used when the conditions are suitable.

Position of Fans.- This method of providing fresh air for the workmen does not expel the noxious gases from the tunnel and if no other means is provided the fresh air liberated from the tools and engines will not clear the headings but only dilute the fumes already there. To provide a suitable method of driving out the gases and clearing the tunnel, fans have to be used. They are generally placed near the portal of the tunnel and exhaust the gases through a suitable pipe laid along one side of the passage way.

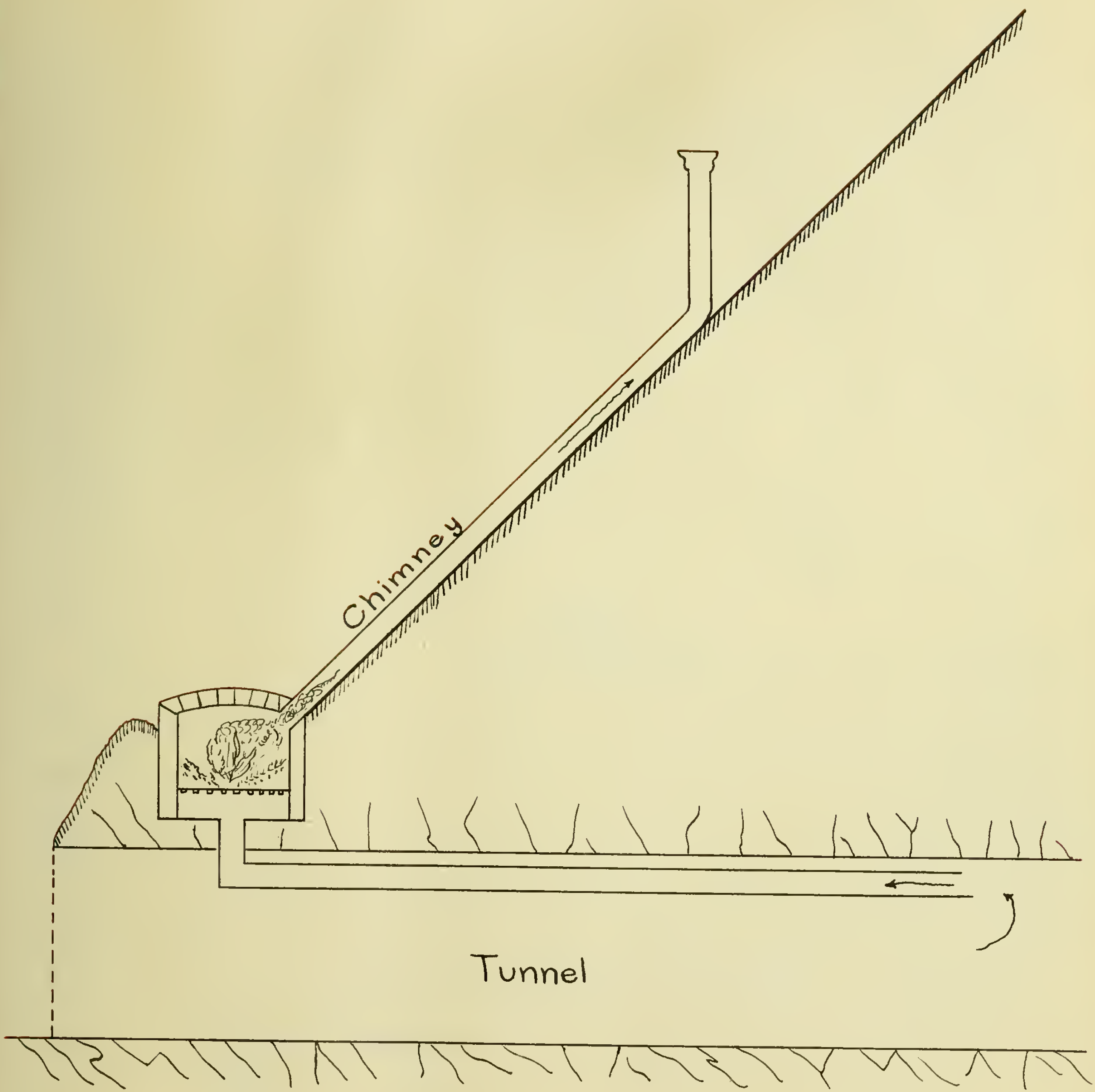
Another method is where the fans located near the portal force pure air through the side gallery and then back through the main tunnel to the portal. If one or more shafts are used in the construction of the tunnel, fans can be installed near the mouth of the shafts and ventilation provided for in that way. The general principles involved in this form of ventilating are, that the exhaust from the different air tools and engines be sufficient to provide a clear atmosphere in the tunnel, and that the air currents from the fans be sufficient to cool the headings and drive the vitiated air form the tunnel. Where this system is used during construction the most advanced headings as well as the remainder of the tunnel can be cleared quickly and the air maintained in a pure condition after the charge has been fired. This method of ventilating was illustrated in connection with the Simplon tunnel so no further examples will be

cited.

FURNACE AND CHIMNEY.- The furnace and chimney have been used to a slight extent to ventilate tunnels during construction, but at present this method is not often employed. The theory of this form of ventilation is to rarefy the air near the bottom of the shaft or chimney, thus producing a steady current which draws the vitiated air out of the tunnel through the shaft or chimney, and causes fresh air to flow in at the portals toward the working face. In order that this system shall work to the best advantage a special plant has to be installed.

Ventilation Plant.- This plant when placed near one end of the tunnel consists of a furnace and chimney, the firebox of the furnace being usually placed a little above the top of the tunnel. When the plant is placed at the bottom of a shaft the arrangements are the same. The only difference is that the shaft takes the place of a chimney.

Air Currents.- The air supply for the combustion of fuel in the furnace istaken through a tight box, opening underneath the firebox and extending into the tunnel to the heading. This box is suspended from the ceiling of the tunnel. The operation of this system is quite simple. The fire in the furnace creates a draught up the shaft or chimney and the air to produce combustion is drawn from the interior of the tunnel through the box. In this manner a complete circulation of the air currents is provided for. The fresh air enters at the portal, passes through the tunnel toward the working face, and returns along the top through the box into the furnace and out through the chimney.



Furnace and chimney used in ventilating
MONT CENIS TUNNEL

Fig.- 1

Mont Cenis Tunnel.- The Mont Cenis tunnel, which is one of the many alpine tunnels, affords a good illustration of this method of ventilating. An incline chimney was constructed 20 or 30 feet from the tunnel entrance.(See figure I.)This chimney is 40 inches square, and is built up the slope of the mountain at an angle of 45°. The upper part is vertical. At the foot of the chimney is a large furnace, the fire grate of which are placed a little above the roof of the tunnel. The air is supplied to the fire through a tight wooden box opening underneath the fire grate and extending into the tunnel, where it is suspended from the ceiling. The operation is similar to that already described. This plant was very successful in clearing the smoke from the tunnel during construction.

Moorhouse Tunnel.- This system of ventilating also gave good results at the Moorhouse tunnel on the Railway between Lyttleton and Christchurch in South Island, New Zealand, built about 1865. The upper portion of the tunnel was partitioned off by a floor or brattice about 9 feet above the rail level, forming a connecting flue with one of the shafts, which, by rarefying the air, caused a steady current up the shaft and drew the smoke away from the working face.

PERMANENT VENTILATION OF COMPLETED TUNNELS

PERMANENT VENTILATION.- The permanent ventilation of completed tunnels is a question that has become more prominent in later years than ever before in the history of railroads. In former years after the tunnel was completed and opened to traffic, natural methods of ventilation were resorted to almost entirely. Some of the longer and larger tunnels were provided with ventilating plants, but these in most cases were designed improperly, and at times were inadequate or else were thoughtto be uneconomical and not operated as they should have been. This made the existing conditions little or no better than they would have been if no artificial methods were employed.

IMPROVING VENTILATION.- In recent years the large increase of the traffic over the different roads, together with the increase in coal consumption of the modern locomotives, has lead to the adoption of improved systems of ventilating. In tunnels that in former years were sufficiently ventilated by natural methods, it has become necessary to provide artificial means of ventilation, due to the frequency of trains passing through them. The air in these tunnels, during the years when traffic was comparatively light, was sufficiently pure in insure safety, but became vitiated by the increased quantities of fumes arising from the combustion of larger quantities of coal and necessitated the use of other means of purifying the air than could be employed under the most favorable conditions of natural ventilation.

These same conditions have also occured in tunnels that were

mechanically ventilated. The plants at first were able to clear the tunnels of smoke under the conditions that existed, but were inadequate to keep the tunnels cleared after the traffic had increased beyond a certain point. To get rid of the smoke nuisance caused by the increase in traffic, transportation companies sought improvements in ventilating in two ways, by the indirect method and by the direct method.

DIRECT METHOD.- In the indirect method of ventilating the aim was to get at the source of noxious gases, and to decrease the causes that produced them. The first step in this direction was to abandon the use of soft coal on the locomotive and to substitute the anthracite in its place. This in turn was replaced by coke and a little later liquid fuel was adopted. This last method proved to be fairly successful, but conditions have called for even better results. While the smoke nuisance was practically overcome by the use of the latter fuel, the noxious gases were still present and the conditions were little if at all improved so far as health conditions were concerned. This led to the last resort, the substitution of electricity as a motive power through the tunnel. From all indications it is by far the most successful with regard to ventilation.

INDIRECT METHOD.- In the indirect methods of ventilating, the transportation companies have installed large mechanical plants, or have increased the power of those already in, thus furnishing a positive and well controlled ventilation.

For further convenience the subject of ventilating completed tunnels will be divided into two parts, the natural and the artificial methods.

NATURAL VENTILATION

Classes of Tunnels.- The completed tunnels that are ventilated by natural means are separated into two classes. The first class is composed of the tunnels that depend upon the action of the wind to drive out the gases. The other depends upon one or more shafts, the piston action of trains passing through, and the difference in the temperature between the exterior and the interior of the tunnel.

Short Tunnels.- In the first class the tunnels are usually short, not over 3000 feet long, and depend upon the direction of the wind, position of the portal, and the grade of the tunnel for their ventilation.

Effect of the Direction of the Wind.- If the wind is blowing toward the portal, the tunnel is supplied with a large quantity of fresh air and the interior is cleared shortly after the passage of a train in either direction. The wind blows straight through from one end to the other and drives out all the gases. If the wind blows across the portal perpendicular to the axis of the tunnel the existing conditions after a train has passed is not so good. In this case no general current of air passes through the tunnel from end to end and it is likely to remain full of smoke for some time unless the currents of air produced by the piston action of the train are of sufficient strength to clear it. This is generally the case in short tunnels but the time required is considerably longer than when the wind blows out all the gases directly.

Position of Portal.- When the ventilation of the tunnel depends upon the wind the position of the portal is an important factor. If the portal is located in a deep cut, its position may be such that only winds blowing directly along the center line of the tunnel can reach it, and these winds may blow only during certain seasons of the year. If the portal is exposed the chances of proper ventilation are better. The ventilation in this latter case is aided by the wind to some extent no matter in what direction it may be blowing.

Grade.- Another item that is important in the ventilating of this class of tunnels, is the grade of the tunnel. If the wind is blowing up the grade, the tunnel is easily cleared of all smoke and gases. The reason for this is that the tunnel resembles in some respect a long chimney and the hot gases emitted by the locomotive in passing through the tunnel, tend to flow toward the higher portal. Now if the wind is blowing in that same direction it is evident that the smoke will be quickly expelled from the tunnel. Such is not the case when the wind is blowing down the grade. The hot gases tending to flow toward the higher portal meet the wind blowing in the opposite direction. The result is two opposite forces acting against each other. If they are both equal the tunnel will not be cleared until the gases have cooled and the wind has forced them out through the lower portal. This requires a longer time than if the wind had been blowing in the opposite direction. Then again if trains should follow each other through the tunnel in rapid succession, the interior of the tunnel would be completely filled with smoke until such a time when there was cessation of traffic of

sufficient duration to allow the gases to flow out. This cessation might not occur for several hours, but, as the time required for a train to pass through the tunnel would be comparatively short, one or two minutes, no ill effects would be felt by the train crew and passangers.

Long Tunnels.- When the question comes up of ventilating long tunnels that contain one or more shafts the conditions involved are somewhat different. In long tunnels it is almost essenti al that the tunnel shall be cleared of the smoke emitted from one train before the next is allowed to enter. If the traffic is light, sufficient time may be provided between trains to accomplish this, but if the traffic is heavy and it becomes necessary to run trains in rapid succession the natural means of ventilating may not be sufficient, and artificial means must be employed.

One Shaft.- If the tunnel has only one shaft open for ventilating purposes it is preferable that the shaft be located as near as possible to the center of the tunnel , and that the grade of the tunnel shall slope down from this central position towards each portal. The reason for this is apparent. When the interior of the tunnel is warmer than the outside atmosphere, the air currents will flow up the shaft. The shaft when placed in a central position with respect to both portals will draw the air and gases from each end of the tunnel with an equal intensity. This clears both ends of the tunnel at the same time. If the temperature of the tunnel is cooler than the outside atmosphere, the air currents will be reversed. The fresh air goes down the shaft and drives the gases from the tunnel throughboth portals.

Theoretically, this is what happens, but actually the eddy

currents, and the piston action of trains passing through the tunnel , have to be considered. These produce cross currents, and engineers who have studied the subject differ as to the ad- visability of using one or more shafts to promote natural ventilation in a long tunnel. If shafts are used at all, one is preferable to two or more.

Two or more Shafts.- If two or more shafts are used they should be spaced equal distances apart throughout the tunnel. When only two are used they are generally spaced about one third the length of the tunnel from each portal.

In the case of a tunnel with two or more shafts the general directions of the currents will be the same as explained above for one shaft when the air in the tunnel is not agitated by the passage of a train. If the general direction of the air is up the shafts, the air in the tunnel being warmer than that of the outside atmosphere, and a train enters one end the result is as follows: The train entering the tunnel acts similar to a piston and forces considerable air in front of it, and tends to produce a general current in the same direction as that in which it is traveling. The air pushed in front tends to escape up the first shaft, carrying with it any gas that may at that time be in the tunnel. The smoke from the engine, due to the other current mentioned, tends to follow the train. Now when the train has passed under the first shaft the suction tends to draw the gases back down the shaft, thus reversing the air currents previously started. These same effects happen at all the shafts, producing many eddies and cross currents, so that after the train has finally passed through the tunnel, the air and gases are consider-

ably agitated but have no general flow in any direction. The only portions of the tunnel that are cleared of smoke are the two end sections between the first shaft and the portal, the remainder of the interior is usually filled with smoke for a considerable time after the train has gone through. This time is dependent upon the atmospheric conditions, or the time required for the air currents to readjust themselves and flow in the same direction as they did before the train passed through. In some tunnels the entire section between shafts has been known to remain full of smoke for several days.

Advantage of One Shaft.- At present one shaft in a tunnel is preferable to two or more, and some of the tunnels that formerly had several shafts for ventilating purposes are being changed. That is, the shafts are filled up and the ventilation depended upon by the piston action of trains, or only one shaft is left open. The advantage is in favor of one shaft, for when only one shaft is used in the tunnel there are fewer cross currents and eddies after the passage of a train and the tunnel sections between the shaft and each portal tend to clear themselves similar to that where two or more shafts are used. The advantage is that there is no space between shafts which will remain full of smoke. It is also cheaper to keep only one shaft in repair than several. The cost amounts to considerable when the shafts are deep and lined with stone or brick.

CONDITIONS THAT EFFECT VENTILATION.- Whether the tunnel uses one or more shafts in its ventilation there are several conditions that usually aid or retard the proper ventilation of the tunnel. These conditions are temperature, wind, and the piston

action of trains mentioned above.

Temperature.- The temperature is an important factor to be considered when natural ventilation is desired. It is the difference in temperature between the exterior and the interior of the tunnel that causes air currents to pass up or down the shafts. If the outside andinside temperatures are the same there are no currents. When such conditions as these exist and a train passes through the tunnel emitting considerable smoke, this smoke will move backward and forward in the tunnel, due to the eddies and cross currents, but very little of it will find its way out. The result is that the tunnel will remain full of smoke and the next train going through will have both its own gases and those already filling the tunnel to contend with. The danger of accidents under these conditions is more likely to be present because the engineer is unable to see more than a short distance ahead of his own train.

Wind and Trains.- The effects of the wind blowing in at the portal, and the piston action of trains going through the tunnel have been mentioned before so these two conditions will not be further discussed.

Several examples illustrating the ventilation of completed tunnels by natural means will now be given.

Box Tunnel.- The Box tunnel between Chippenham and Bath on the Great Western Railroad is 9600 feet long, 30 feet wide, 24.5 feet high above the rails and has a 1% grade from one end to the other. In the original work of construction seven shafts were used but two of these were closed soon after the tunnel was completed, leaving five open for ventilating purposes. These

shafts were 25 feet indiameter and widened out to the full width of 30 feet where they intersected the tunnel. They were all lined with brick. The deepest shaft was about 300 feet.

The ventilation of this tunnel depended a great deal upon the weather. If a strong wind was blowing, the smoke escaped very quickly, but in foggy weather it at times became troublesome. The conditions, however, were not so bad but that work could be done at all times in the tunnel. When a train passed through the tunnel going down grade it produced no perceptible effects upon the air, but ascending trains generally filled the interior with smoke. This tunnel depended mostly upon the quick passage of trains down the grade for its proper ventilation, and it was found that the shafts impeded rather than assisted the work of clearing the tunnel of gases. The men in charge of the tunnel would have preferred to close all the shafts and to depend for ventilation upon a natural current from end to end caused by the difference in temperature, prevailing winds, and the piston action of trains.

Sapperton Tunnel.- The Sapperton tunnel between Sivindon and Gloucester on the Great Western Railroad is one mile long, 28 feet wide and 20 feet high. The tunnel is built upon a 1.4% grade.

Several shafts were used in the original construction but all of these have been closed with the exception of one. This one is planked across its lower end where it coincides with the top of the arch, leaving only a small hole four or five feet square. This tunnel does not depend upon the single shaft for ventilation, but upon the piston action of trains going down the grade.

When a heavy freight ascends the grade through the tunnel it is usually assisted by a pusher engine and this engine is run down the grade as soon as the train has passed up. This assists in clearing away the smoke but a passenger train running down the grade at a high speed is found to be far more efficient and is indeed the only effectual ventilation. If no trains pass down the grade after a heavy freight has ascended, the smoke will remain in the tunnel for hours.

Conclusions.- Summing up the conclusions drawn by engineers who have had charge of tunnels ventilated by natural means, it is seen that numerous shafts are quite unnecessary for ventilation. The actual ventilator is a fast train passing through the tunnel, and the shafts only interfere with the natural currents which sometimes flow through. The limit in the length of tunnels that can be ventilated by natural means is probably 3000 feet. If the traffic is light, natural ventilation may be employed in tunnels of twice that length, but under conditions of heavy traffic all tunnels over 3000 feet should be ventilated by artificial methods.

New York Subway.- Another example of natural ventilation is the New York Subway. Although many subways are now provided with some system of ventilation requiring the use of fans, by far the greatest number depend for a circulation of air upon currents set up without special mechanical aid. The New York Subway is a good example of this class.

The ventilation is accomplished by the use of blow holes or free openings to the outside air, and the current that passes through these openings is sometimes violent. The term blow hole

includes all openings through which the confined air can escape and through which fresh air enters. These openings are found in the roof of the tunnel, in side chambers, and in the stairways. Observations nade with anemometers showed an average velocity of 16 1/2 miles per hour through the stairways, and if this current were present in half the openings the quantity of air so supplied would have been sufficient to renew the entire air in the subway every few minutes.

To provide for a suitable and reliable movement of the air, a careful study of the direction of the openings with respect to the wind is necessary. This is provided for by a cowl-like kiosks, so that whatever direction the wind may be blowing the fresh air always enters these openings and drives the foul air out through others. These latter are arranged in such a manner that the wind always blows on the back of the hood and the piston action of trains drives the foul air up through them.

By this method a wind traveling at a velocity of 25 miles per hour or 36 feet per second, a common occurence in New York at some seasons of the year, will have a pressure of about three pounds per square foot. A wind of 45 miles creates a pressure of ten pounds. When a breeze of 2 1/2 miles per hour acts full upon the kiosks, measuring 5 1/2 x 7 1/2 feet, over the New York Subway, it is as effective as two fans, each six feet in diameter turning at the rate of 200 revolutions per minute and delivering 21200 cubic feet of air per minute.

In the New York Subway the piston action of trains is the more important factor in establishing a circulation of air through the blow holes. The principle of the piston action is

as explained above for tunnels containing two or more shafts.

Observations made in the Subway with the ordinary train service of early afternoon showed that the air passed from one station to the other at the maximum rate of eight miles per hour. The average rate was three miles per hour. The approach of a train toward a station could be felt by the flow of air ahead, when the train was over 1000 feet away. In this connection the express trains were of special service in the ventilating. The reason for this was that they passed through the local stations at full speed and by their high velocity caused especially energetic currents of air to pass in and out of the openings of the stairway and roof.

This method of natural ventilation of the New York Subway has given good satisfaction. During all the hours of the day the air in the subway is fresh and cool.

ARTIFICIAL VENTILATION

SACCARDO SYSTEM.- The Saccardo system of artificial ventilation is named after Marco Saccardo, a prominent Italian engineer, who first conceived the idea of ventilating tunnels in this manner, that is, of forcing air into one portal entrance thus causing another current of air to be induced in the tunnel. This system of ventilation was first tried at the Pracchia tunnel on the railroad between Florence and Bologna in Italy. This tunnel is 9000 feet long, single track, and has a grade of 2.5 percent. Before the Saccardo system of ventilation was used, the tunnel was ventilated solelyby natural means. Under any condition of wind the air in the tunnel was bad, but when the wind was blowing at the lower end at the same time a train was ascending the grade the conditions of the air became unbearable. Several accidents that have resulted in this tunnel on account of these existing conditions were mentioned in the introduction.

After the tunnel was equipped with the Saccardo system several experiments were made to test its efficiency. Before starting the fans the tunnel was filled with smoke from end to end. The temperature was 107° F., with 97% of moisture, or nearly complete saturation. With the fan running the temperature in the tunnel fell to 80°,- that of the external air. The moisture in the tunnel was normal. The amount of air propelled by the fans was 164000 cubic feet per minute together with 46000 cubic feet resulting from the induced currents, making a total of 210000 cubic feet

of air passing through the tunnel per minute at a water pressure of one inch.

Ventilating Plant.- In the Saccardo system of ventilation the plant is placed at the portal of the tunnel, usually on the up grade end, and the air is blown down the incline against the ascending traffic. No shafts are required as all the apparatus is placed at the portal and the expense of installation is comparatively small.

The method of operation is quite simple. A motor is used to propel the fan and the air from the fan is forced through a sort of nozzle which extends clear around the angular space between the gauge of maximum construction and the interior section or intrados of the arch. This air going through the nozzle at a high velocity causes a current of air to be induced through the portal.

Advantages of this System.- This system of ventilating has several advantages. The air being blown down the tunnel against the ascending traffic clears away the smoke and gases from the engines and supplies the engineer and fireman with fresh air, thus eliminating the danger of accidents due to the suffocation of the men on the engine.

The position of the plant is another advantage. By this arrangement shafts are not necessary. It also does away with installation of the plant either at the base or top of the shaft where it is very inconvenient to the tender. Then again the system is very efficient as the volume of air entering the tunnel from the fan produces an induced current from the open mouth of from 30 to 100% according to the arrangements made.

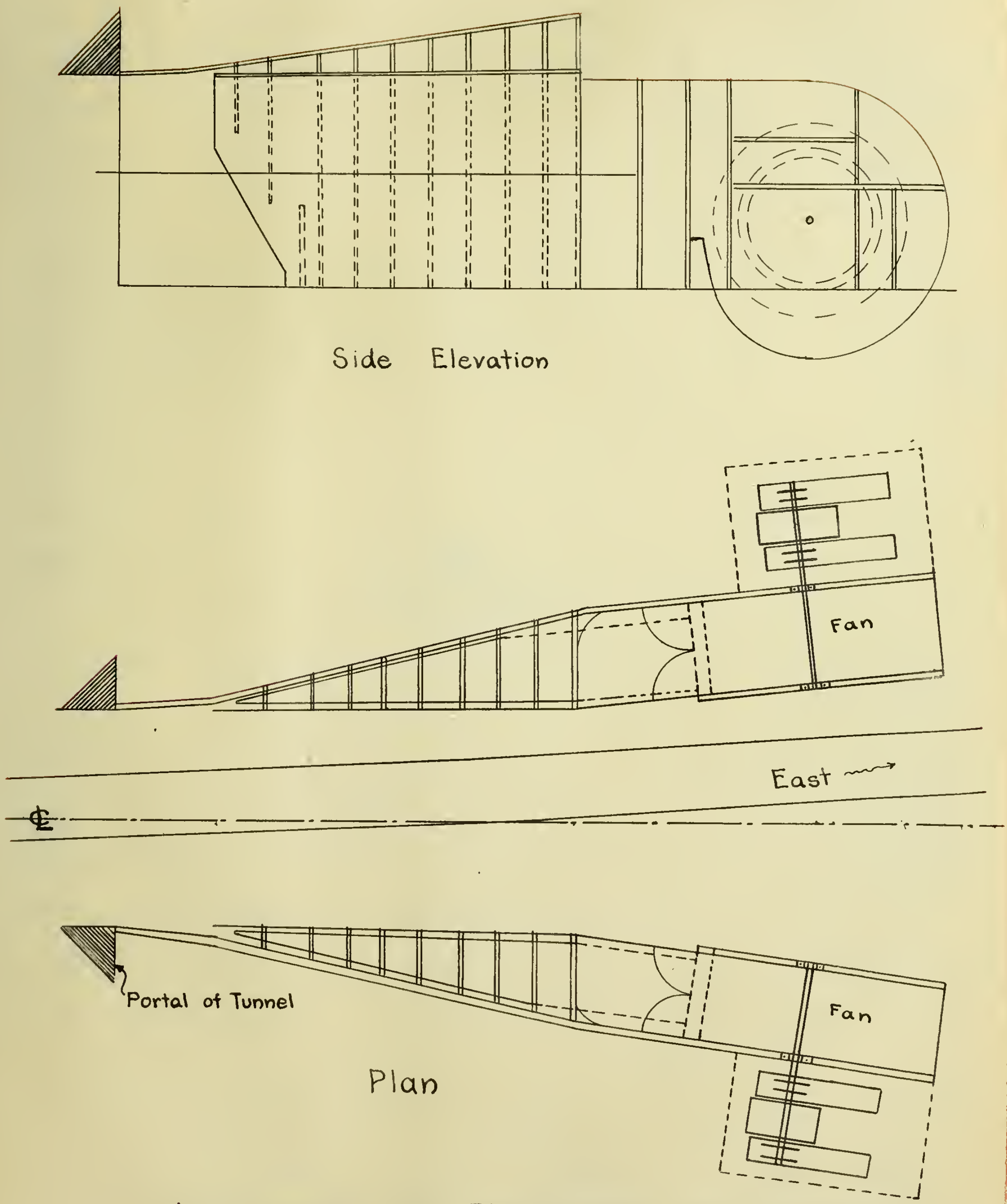
Adapted to Long Tunnels.- The Saccardo system of ventilation is especially adapted to long tunnels that contain no shafts, or where the shafts were afterwards covered over. This system is not applicable to subways, as the smoke would simply be blown to the next station, just where everything should be clear.

Examples.- Some of the tunnels that use the Saccardo system of ventilation are: the Pracchia tunnel mentioned above, St. Gothard tunnel, on the St. Gothard Railway from Lucerne to Milan, Giovi tunnel north of Geneo, Italy, Big Bend tunnel on the Chesapeake and Ohio Railway, and the Elkhorn tunnel on the Norfolk and Western Railroad.

St. Gothard.- The St. Gothard tunnel is 9.3 miles long and 26 feet wide. This tunnel was provided with a Saccardo system of ventilation by M. Saccardo, in 1899. The plant was installed at the north end of the tunnel and delivers the current of air in the same direction as the natural currents flow. This plant, which consists of two blowers, is capable of producing a current of air through the tunnel with a velocity of 552 feet per minute. This is found to be satisfactory.

Giovi.- The Giovi tunnel was ventilated by M. Saccardo in 1902 and has given good satisfaction.

Big Bend.- The Big Bend tunnel is near Hinton, West Virginia. It is a straight single track tunnel 6500 feet long, 15 feet 3 inches wide and 17 feet 9 inches high and is lined with brick throughout. From the west end of the tunnel there is an ascending grade of 0.4% for two-thirds of the distance, the remaninder of the distance to the east end having a descending grade of 0.08%.



Arrangement of Blast Fans and Nozzle
BIG BEND TUNNEL
Fig.-2

Until mechanical ventilation was installed, in the latter part of 1902, the tunnel was ventilated by natural means, reliance being placed upon two shafts, located about one third the distance from each end, to clear the smoke and gases from the tunnel. After the traffic increased to an average of forty-five trains per day the natural currents were found to be inadequate for clearing the smoke, in fact the gases were very bad and several employees were seriously affected by them. Fig. 2 shows the general arrangement of the ventilating plant, which is at the eastern or upper end of the tunnel. It consists of a nozzle 50 feet long, attached to the east portal the minimum interior cross section of which is the same as that of the tunnel. This nozzle is composed of latticed steel ribs to which are riveted longitudinal channels. This forms the framework and the whole is covered by one-eigth inch steel plates. The inner surface of the nozzle is formed of 3 inch by 6 inch pine sheeting tongued and grooved, put together tightly and attached securely to the outer frame work. All of the wood work is covered with an asbestos paint. The inner end of the nozzle is secured to the tunnel portal and to the outer end are attached the outlets of the fans, one on each side of the track. These fans are 7 feet wide and 14 feet in diameter,each coupled to two 12 inch by 14 inch center crank steam engines. The engines are fed from a battery of boilers located a short distance east of the fans.

At 144 revolutions per minute these two fans deliver into and through the tunnel a total of 300,000 cubic feet of fresh air per minute, the measured velocity of the moving currents in the tunnel being 1200 feet per minute. Under the present

operations these fans are not speeded up except when trains come to the tunnel at either end. The average velocity is then about 120 revolutions per minute, at which rate the two fans deliver through the tunnel a total of 250,000 cubic feet of air per minute. Under the ordinary plan of operation, the tunnel is cleared in from 7 to 9 minutes after the passage of a full tonnage east bound train, the time being dependent upon the speed of the fans. After a west bound train has passed, the tunnel can be cleared in a shorter time.

The result of the installation of this plant has been a prompt clearing of the tunnel after the passage of each train, and a clear, cool atmosphere on the arrival of each succeeding train. In consequence of this the tonnage loading of east bound trains has been increased from 1700 tons, which was the rating before the installation of this plant, to the present rating of 1928 tons.

Elkhorn.- The Elkhorn tunnel, on the Norfolk and Western Railway, is at Coaldale, West Virginia and crosses the Flat Top Mountain at an elevation of 2386 feet. The tunnel is 3000 feet long, 14 feet wide, 19 feet high and is single track between two sections of double track road. The straight portion of this tunnel is 2167 feet long, 833 feet on the eastern end being a 2 degree curve. Thewestern approach is on an up grade of 2 percent and reduces at the portal to 1.4 percent. This rate of grade extends through to the summit located a few hundred feet east of the east portal.

Before going into detail concerning the plant it would be well to fully comprehend the nature of the traffic through this

tunnel and the conditions that existed in the Elkhorn tunnel before the mechanical plant was installed.

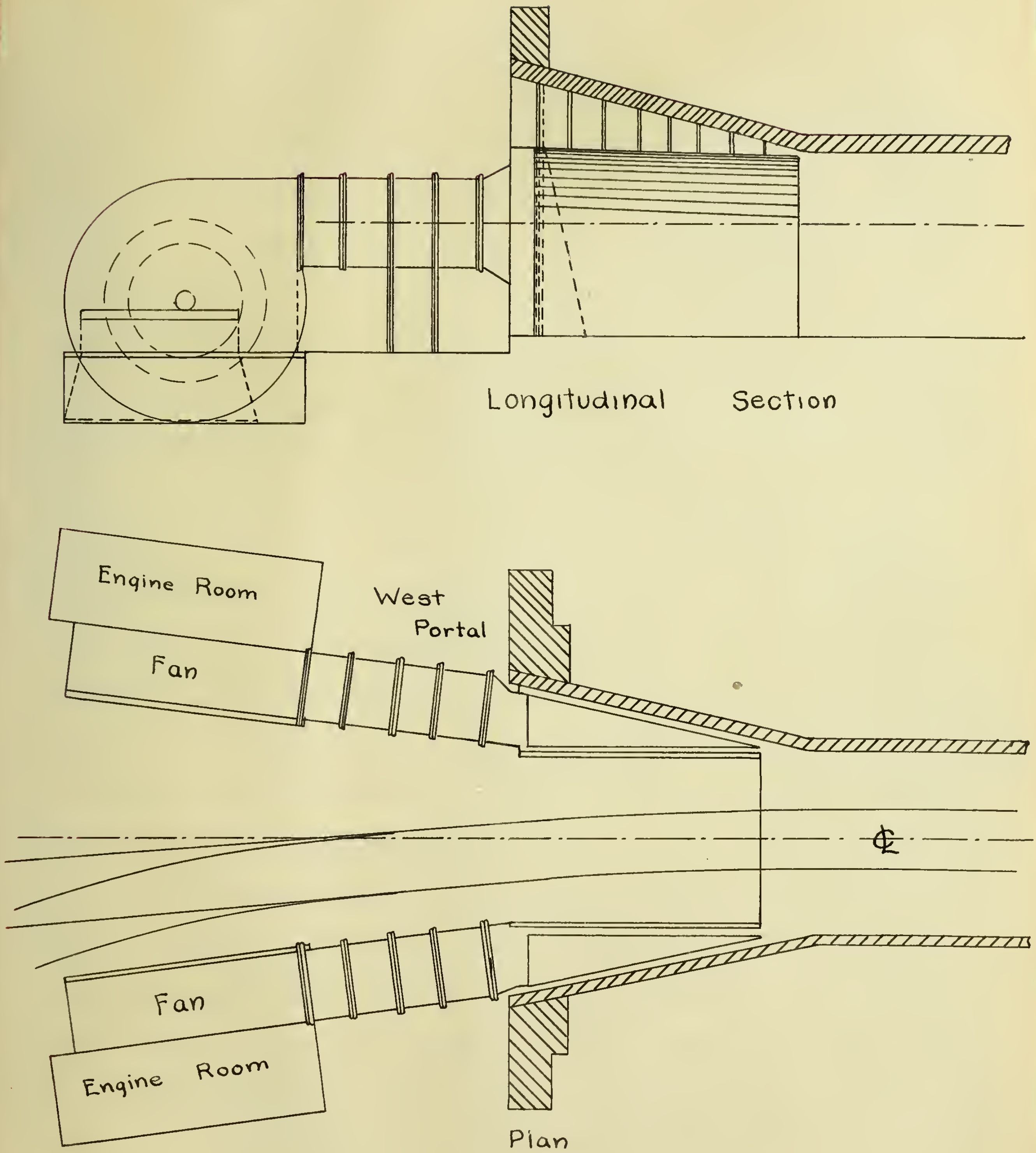
On the west slope of Flat Top Mountain quite a large percentage of coal is mined and shipped east. This necessitates the hauling of all the coal up the adverse grade and through the tunnel. This is accomplished by the use of two or three locomotives to each train of about 1200 tons. When only two engines are used they are placed, one at the head of the train and the other at the rear. In case three are used one is placed in the middle of the train. The records kept at the time of construction of the mechanical plant show that the average number of locomotives that pass through the tunnel every 24 hours approach 100. East bound trains frequently stand at the west end of the tunnel and follow each other through as quickly as they get the signal that the train ahead has passed from the tunnel. The time usually taken is about 5 minutes.

On account of the heavy grade and the number of engines used in a train the quantity of gases emitted is very great. Notes taken prior to ventilation showed that in summer it took from 17 to 55 minutes to clear the tunnel. The shortest time of clearance noted was in winter when it averaged about 20 minutes. It can be seen that when the trains were following each other at intervals of five minutes that each train crew had not only to contend with the smoke of their own train, but also that of the two or three previous trains. The temperature inside the tunnel was about 30 degrees higher than the outside atmosphere due to this improper ventilation. During the four years prior to the installation of the plant 26 men were asphyxiated in the tunnel.

In 1900 the Norfolk and Western Railway decided to ventilate this tunnel and decided that the best plan to secure the desired positive results was to ventilate it from one end by blowing fresh air through the whole tunnel. The essential features of the plant are: the fans of proper dimensions and speed installed at one end of the tunnel for driving fresh air into it at the pressure determined upon, and the funnel shaped nozzle. This nozzle was constructed in such a manner as to preserve the cross section of the tunnel and at the same time provide a reduced area of outlet through which the fresh air can be forced with great velocity. The air is required to leave the nozzle at a high velocity in order to insure its passage through the whole length of the tunnel.

The plant was located at the west portal. The reason for this was because the east bound freight trains have two or three engines, as described above, and it was desirable not only to clear the smoke quickly but also to force it away from the cabs and protect the engineer and firemen from the smoke of their own engine. The blast was therefore planned of sufficient strength to drive the gases in front of each east bound engine, instead of permitting it to trail back into the cab.

Fig. 3 shows the general arrangement of the plant. The plant consists of two fans 14 feet in diameter and each operated by an engine of 75 nominal horse power. The boiler room was located on one side of the track west of the fans. The fans are capable of making 140 revolutions per minute and deliver air through the nozzle at the rate of 200,000 cubic feet per minute, or an average velocity of 1700 feet per minute through the tunnel. The



Arrangement of Fans and Nozzle at West Portal
ELKHORN TUNNEL

Fig.-3

fans are arranged so that they are controlled by a valve in the boiler house, and the whole plant operated from one point.

In 1901 several tests were made to determine the condition of the air in the tunnel during the passage of a heavy freight train. A three engine east bound freight loaded with coal passed through the tunnel in 6 minutes while the fans were running at 142 revolutions per minute. The observer on the first engine rode on the tank and reported the tunnel clear two thirds of the way through, and that there was no objectionable smoke anywhere. An observer at the east portal reported that the smoke of the train came out two minutes ahead of the first engine. The observer on the second engine reported the air clear behind and that he could see seven car lengths ahead of the engine. The observer on the rear engine rode in the cab with the windows open and found the tunnel practically clear and no smoke behind, showing that fresh air was with the engine throughout.

Conditions of operation of this tunnel are somewhat similar to those of the Big Bend tunnel, that is, the fans are run slow and only speeded up when a heavy train is about to ascend the grade through the tunnel. In the Elkhorn tunnel the fans are kept moving at not more than 30 revolutions per minute which is sufficient to keep the tunnel clear and cool except when trains are approaching from the west. West bound trains, on account of the down grade, emit very little smoke so that 30 revolutions per minute is sufficient to keep the tunnel clear and cool under those conditions. On the approach of an east bound train the fans are run at about 140 revolutions per minute. This speed is maintained until the operator at the ventilating plant gets the

signal by the track circuit that the train has cleared the tunnel. The fans are then again run at not more than 30 revolutions per minute.

The results that have been obtained at this tunnel are good. The tunnel is always free from smoke and the air cool regardless of the number of engines used or the frequency of the trains.

The condition of the rails has been improved and the tonnage loading of the trains has accordingly been increased. Track men now prefer the cool atmosphere of the tunnel than that outside, just reversing the conditions that formerly existed. After a train has passed through the tunnel, east bound, it seldom happens that smoke is seen coming out of the east portal longer than one minute after the clearance of the train, and in good weather the tunnel is clear when the train leaves it.

EXHAUST CURRENTS FROM FANS.- When completed tunnels are ventilated by the exhaust currents from fans, the ventilating plant is usually installed near a central shaft, or at each portal, as in the case of the Boston Subway. This latter position requires several accessories and will be described later in the ventilation of the East Boston tunnel.

Position of Fan.- If the fan is installed at the central shaft it is preferable that its location be near the bottom. The advantage in placing the fan near the bottom instead of at the top of the shaft is that it is easier to operate. If the fan was located at the top of the shaft there would be a tendency on the part of the operator to neglect its proper care. A trip up the mountain in all conditions of weather would not at all times be desirable. However, if it is placed near the bottom it is always

accessible and more convenient for the tender.

Method of Ventilating.- The method of ventilating a tunnel by the exhaust currents from a fan practically explains itself. The fans are run usually by a motor in such a direction as to exhaust the air from the tunnel and force it up the shaft. This cause fresh air to enter at both portals and provides a complete circulation.

Arrangement of Fans.- The fans are often arranged so that the air currents can be reversed, forcing the air out through both portals and drawing in the fresh air through the shaft. However, the former method is the more economical and is the one generally used.

Hoosac Tunnel.- The Hoosac tunnel, on the Boston and Maine Railroad, is ventilated in the mannerdescribed above. This tunnel is 4.7 miles long, 25 feet wide and 22.5 feet high. From each end there is a rising grade toward the center of 0.5%, where there is a shaft 1028 feet deep. The shaft is elliptical in section with diameters of 15 feet and 27 feet. Doors are placed at the portals for use in winter to prevent ice forming in the tunnel.

This tunnel was originally intended to be ventilated by natural means but the increase in traffic necessitated the use of an artificial method for clearing the smoke. Under natural conditions the shortest time required to clear the tunnel by means of the shaft was observed during the winter seasons. The time then observed after the passage of a train until the tunnel was cleared of smoke was 20 minutes.

The ventilating fan was installed at the top of the shaft

and arranged so as to draw the smoke and gases through the shaft. This fan was operated by a 125 H.P. electric motor, the current being supplied from North Adams, 5 miles distant.

Boston Subway.- The Boston Subway Tunnel is about 1.8 miles long and has one double track section and a four track section. All the trains in this tunnel are operated by electric power.

This tunnel is ventilated by exhaust fans set in chambers adjoining the tunnel and spaced about midway between stations. These fans are vertical and placed directly against the openings connecting the fan chamber with the tunnel. The air is thus drawn from the tunnel and generally discharged upwards through gratings in the street sidewalks, except in two cases where they discharge through low shafts. Fresh air enters at the stations and flows each way to the fans. These fans are designed to move the air in the subway at a velocity of 60 feet per minute and to change the air every 10 minutes.

The section between Park Street Station and Boylston Station is four track, its cross section is 707 square feet and the distance between the centers of the stations is 1250 feet. This section which contains 884,000 cubic feet is ventilated by two fans placed midway between the stations, each having a diameter of eight feet and a rated speed of 225 revolutions per minute. The ventilation of this Subway Tunnel is said to be good.

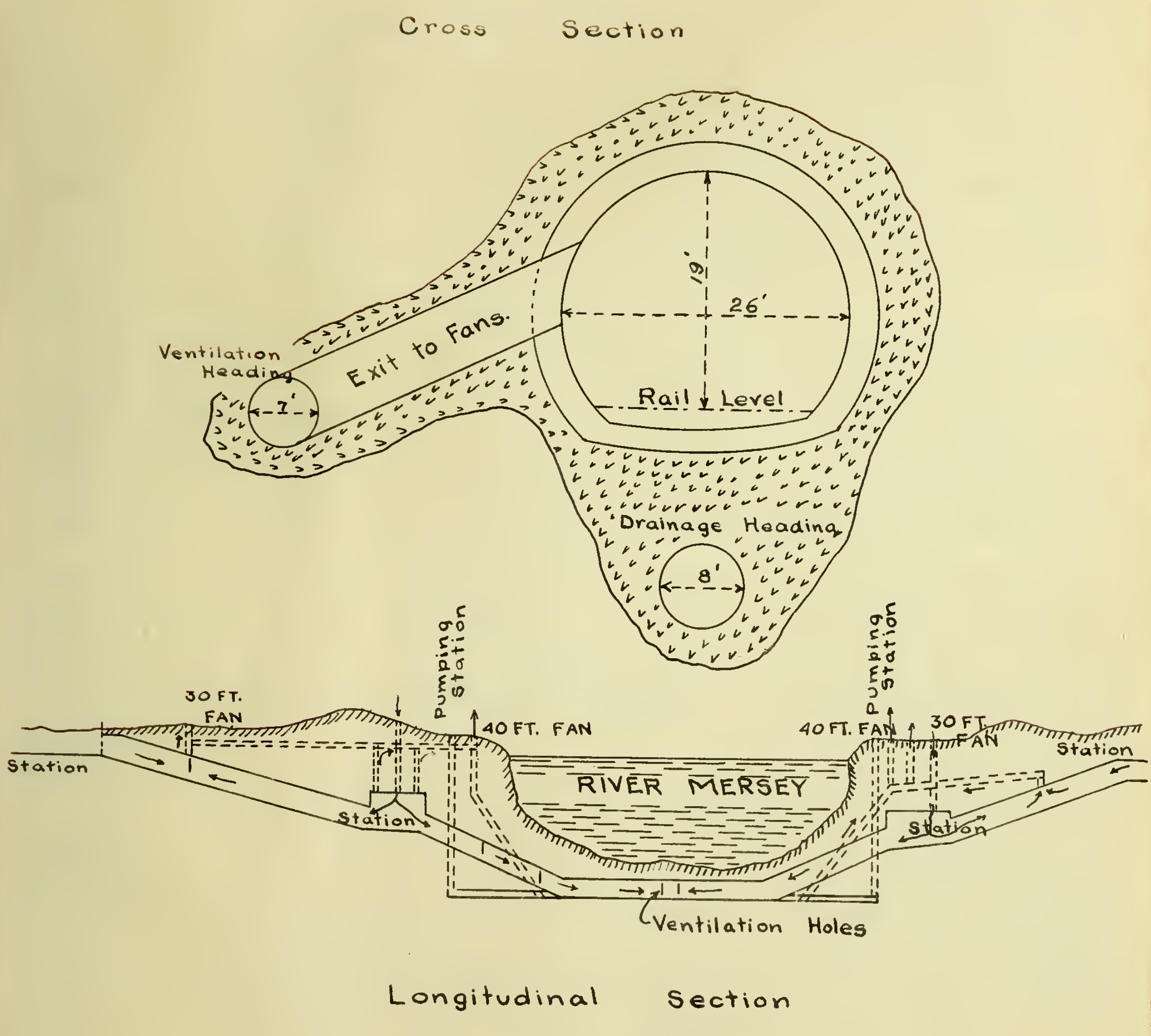
East Boston Tunnel.- The East Boston Tunnel had to be ventilated somewhat differently than the Boston Subways on account of its harbor portion. All trains are operated by electric power, the same as in the Boston Subway. The double track under the harbor is 23 1/3 feet wide at the springing line of the

arch and has a total cross section of 332 square feet.

The harbor section of the tunnel is provided with a shaft at either end containing the exhaust fans, which are located near the surface. In the crown of the tunnel is a duct with a cross section of 48 square feet. This duct is made by using a diaphragm one inch thick, constructed of expanded metal and concrete, and suspended to the crown of the arch by steel rods and plates incased in the concrete. In the middle of the tunnel a partition divides this duct into two parts and on each side of this partition there are 14 openings, each four feet long and 1 foot 5 inches wide. There are other groups of openings at intervals of 550 feet, the number diminishing as they approach the fan chambers. The ventilating duct is curved downwards for the central two thirds of its span. The side portions are flat and it is in these that the openings referred to are located. All the openings are fitted with doors and can be operated from the tunnel below. When the movement of the air in the tunnel is not affected by the wind the two groups of openings near the center are alone used.

The ventilation of the tunnel is accomplished in the following manner. The fans running as exhausts draw fresh air into the portal at East Boston and through the station at Atlantic Avenue on the Boston side. This fresh air from both ends passes to the middle of the tunnel and is drawn into the ducts through the openings. The air then passes back through the ducts and out through the fan shafts at either end.

Mersey Tunnel.- The Mersey Tunnel under the River Mersey between Liverpool and Berkenhead, England is a good example of



MERSEY RAILWAY TUNNEL

Fig - 4

successful ventilation under heavy traffic and grades. This tunnel is 4960 feet long under the river, 26 feet wide, and is double track throughout. The grade in a portion of the tunnel is 3.5% or about 196 feet to the mile. The principle on which the ventilation was planned was to admit fresh air in at the stations, and draw it either way to points midway between stations, where the ventilating fans are placed.

An auxiliary tunnel or air drift, 7 feet 2 inches in diameter, runs parallel with the main tunnel, and is connected with it and the stations by sliding doors so that air can be drawn from any point desired. The fans are four in number, two 40 feet in diameter and 12 feet wide, and 32 feet in diameter and 10 feet wide. Their collective capacity is 500,000 cubic feet per minute when running at the average speed of 45 revolutions per minute.

For purposes of ventilation the tunnel is divided into four sections, one fan being alloted to each. By means of the doors in the air passage the fans can be made to do each others work, so that no complete stoppage of ventilation is possible unless all four fans should break down at the same time.

This tunnel has been successfully ventilated by this plant. When the fans were first installed an average of 300 trains passed through the tunnel per day, making an average of one train each way every five minutes. Since then electric equipments have been installed for operating thetrains and the volume of air required has been much decreased.

See Fig. 4 for a general arrangement of the fans and the direction of the air currents in the Mersey Tunnel.